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Lithostructural Control of the Gold Mineralization of the Douta Permit of African Star Resources (Kédougou-Kéniéba Inlier, Southeastern Senegal)

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Abstract

The Douta permit of African Star Resources/Thor Explorations, located in the southeast of Senegal, in the Kédougou-Kéniéba Inlier (western part of the West African Craton), is dominated to the East by metasedimentary formations such as greywackes, shales, graphitic shales, quartzites, cherts, claystones and breccias characteristic of the Dialé-Daléma basin. To the West, the mafic formations of the Mako volcanic belt are the most common. Metasedimentary rocks are associated with metavolcanosedimentary terms found at the contact zones between the two (2) Birimian groups. These different geological formations are cut by mafic dolerite and gabbro sills and/or dykes, as well as quartz and microgranite veins. The Douta gold project is crossed from North to South by the MTZ (Main Transcurrent Zone), generally oriented NE-SW and becoming N-S towards the North. The permit is characterized by several shear corridors. The rocks are affected by brittle, brittle-ductile to ductile deformations. The gold mineralization is hosted by a NE-trending shear corridor called the Makosa corridor (Makosa shear zone), therefore sub-parallel to the MTZ. It has a subvertical dip (75˚ to 85˚ to the NW). It is associated with a hydrothermal phase characterized by quartz-sericite-epidote-fine, disseminated pyrite and arsenopyrite ± albite ± chlorite paragenesis. These minerals testify to the existence of a low degree of metamorphism (greenschist facies, epizonal domain) in the area. However, metamorphism reaches amphibolite facies in some places, particularly in the vicinity of intrusive bodies, with the presence of hornblende (amphiboles) and plagioclase. The gold mineralization is mainly hosted by two (2) metasedimentary lithological units: meta-greywackes and shales.

Keywords

Douta, Kédougou-Kéniéba Inlier, Senegal, Metasedimentary, MTZ, Control, Gold Mineralization, Makosa Corridor

1. Introduction

The Paleoproterozoic (Birimian) domain of the West African Craton (WAC) contains numerous economic gold deposits, some of which have been known since antiquity and others exploited since the 20th century, such as the famous Ashanti deposit in Ghana [1]-[7]. Currently, West Africa is one of the largest gold provinces of Paleoproterozoic age, with a production and cumulative resources of over 10,000 tonnes of gold (or 321 Moz) [8]. Thus, the largest deposits that provide the majority of global gold production are orogenic gold deposits and placers and/or paleoplacers [9] [10] [11] [12]. The Witwatersrand gold deposit in South Africa is the largest placer gold deposit currently known (≈90,000 tonnes of gold) [13] [14] [15] [16]. Bache [13], points out that placer deposits account for 67.5% of the world's gold stock, thanks to the phenomenal old placer, the Witwatersrand, which alone is thought to contain almost 58%. Orogenic deposits are those associated with the Eburnean orogeny (2.2 - 1.6 Ga) [17] [18]. These deposits have been the subject of several classifications, the best known of which are those of Milési *et al.* [19], who define five (5) types of deposit according to geometry, host structures and mineral paragenesis; Milési *et al.* [20], who distinguish three (3) categories based on their relationship with the Eburnean orogeny: 1) pre-orogenic deposits, 2) syn-orogenic deposits and 3) late-orogenic deposits [13] [21]-[25]. That of Boyle [21], is based on the nature of the surrounding rock. Bache [13], in addition to the nature of the host rock, also takes into account the geostructural setting and mineralogical association. However, that of Milési *et al.* [20], which takes into account the geodynamic context, is a simplified classification, based on a reference period constituted by the Eburnean orogeny (2.2 - 1.6 Ga) and remains the global model for Birimian deposits on the scale of the WAC.

In Senegal, like several provinces of the WAC, the Kédougou-Kéniéba Inlier (KKI) is also home to numerous gold deposits and resources. This is confirmed by recent discoveries of major new deposits in the KKI. These include the Massawa (Randgold-Endeavour Mining), Makabingui (Bassari Resources), Petowal (Toro Gold) and Boto (Iamgold) deposits. Almost all of these deposits are characterized by their location close to major shearing faults such as the MTZ, the Senegalo-Malian shear zone (SMSZ) and the Sabodala Shear Zone [26]-[34]. Numerous geological and metallogenic studies have also highlighted the close relationship between mineralization and geological structures. For this reason, lithostructural data are an essential lever for characterizing the control of gold mineralization.

The Douta gold project is located in eastern Senegal, in the administrative region of Kédougou, in the Saraya department. More precisely, it is located in the commune of Khossanto, near the villages of Mandankholy, Sambarabougou and Douta (Figure 1).

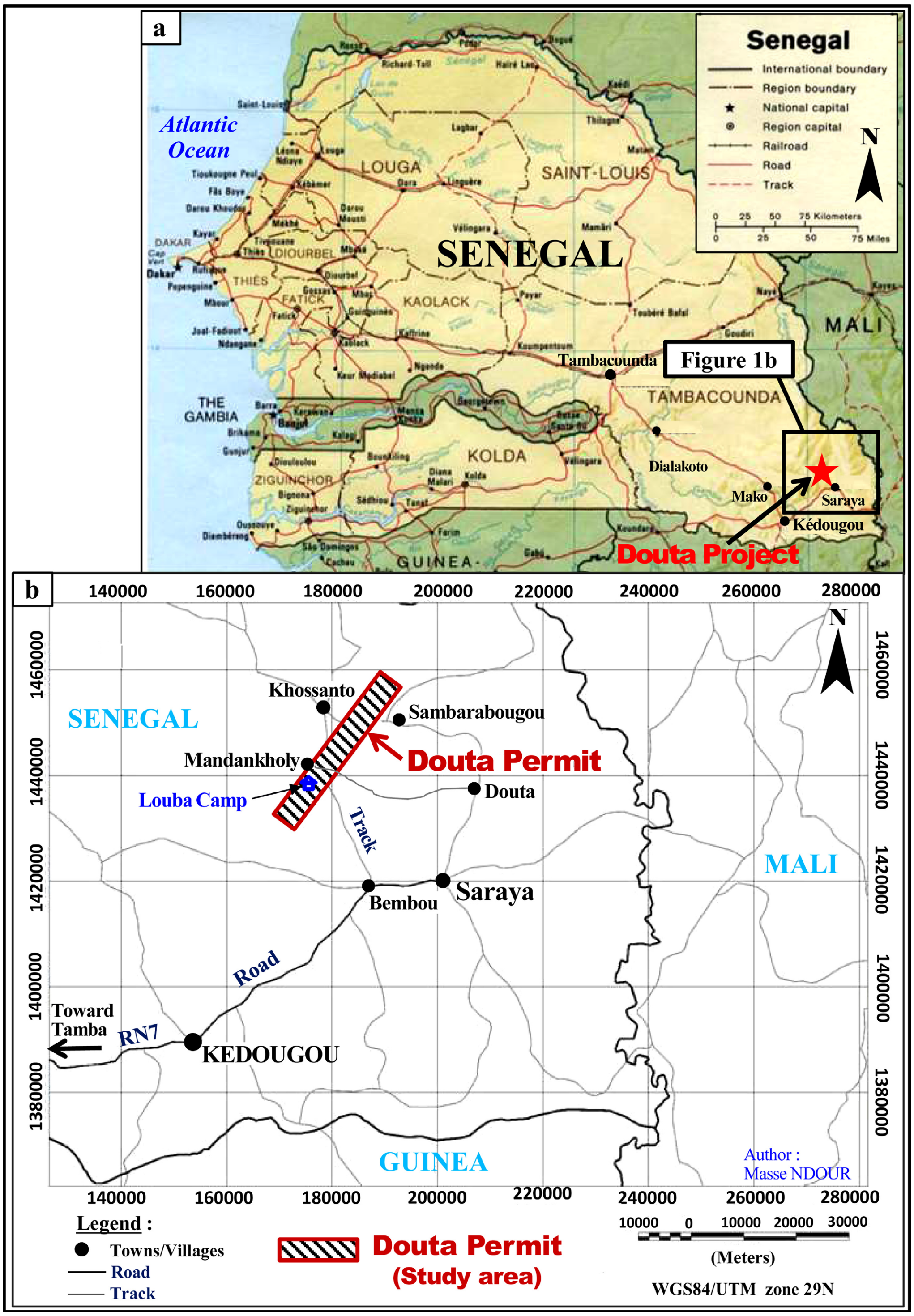

Figure 1. Douta Permit location on (a) map of the republic of Senegal and (b) detailed map of eastern Senegal showing the main localities and access roads.

The aim of the present paper is to define the lithological and structural characters of the geological formations hosting the gold mineralization in the Douta permit and to propose a gîtological model in comparison with other deposits of the KKI and WAC in general. But before that, we will first present the geological context of the study area.

2. Geological Setting

The Douta gold project is located in the KKI, western part of the WAC (**Figure 2**). The latter has been subdivided into three majors Precambrian lithostructural units [35] [36]: 1) in the North, the Reguibat Shield which extends from Mauritania to Algeria; 2) in the South, the Leo Shield which extends over several countries such as Liberia, Sierra-Leone, Mali, Guinea, Ghana, Burkina Faso, Niger and Ivory Coast; and 3) the Kédougou-Kéniéba and Kayes Inliers located between these two entities. The two Shield (Reguibat and Leo) are composed of both Archean (western part) and Paleoproterozoic (eastern part) formations, whereas the Inliers are formed solely of Paleoproterozoic-age terrane. These Paleoproterozoic formations are generally referred to as "Birimian" [1]. The KKI consists exclusively of Paleoproterozoic (Birimian) formations subdivided into two groups separated by the MTZ [19] [37] [38] [39] [40] (**Figure 2(b)**): 1) to the West, the volcanic-dominated Mako group, intruded by the Badon-Kakadian batholith dated around 2199 ± 68 Ma and 2168 Ma respectively by Bassot and Caen-Vachette [41], and Dia [42]; and 2) to the east, the sedimentary-dominated Dialé-Daléma group, cut by the Saraya granite dated at 2079 ± 2 Ma and 2064 ± 30 Ma according to respectively Hirdes and Davis [43] and Delor *et al.* [44], and the Boboti massif dated at 2080 ± 0.9 Ma by Hirdes and Davis [43]. Previous studies [37] [42] [45]-[49] and recent works [40] [50] [51] [52] [53] in the Mako volcanic belt showed the bimodal character of volcanism: tholeiitic in the west and andesitic or calc-alkaline in the east. The majority of gold deposits discovered in the KKI are currently located in this Mako volcanic belt, as clearly illustrated in **Figure 2(b)**. The Dialé-Daléma group, located to the east of the Mako group, is distinguished by its detrital character, with slightly metamorphosed sedimentary formations (metasediments) such as greywackes, shales, conglomerates, cipolins, and so on. Carbonate levels are found mainly in the southern parts of the Dialé-Daléma basin. These are essentially the Bandafassi banded marbles and the Ibel and Boundoukodi conglomeratic marbles.

The study area is dominated to the east by metasedimentary formations (greywackes, sandstones, shales, graphitic shales, cherts, quartzites, claystones, and so on). Volcano-sedimentary terms represented by carbonate and silicate breccias are also very present. These epizonal metamorphic formations are cut by mafic intrusions of dolerite and gabbro. Felsic intrusions are also noted, especially to the NE of the permit, and are related to the late-tectonic Sambarabougou granite [54] located close to the study area. In the western part of the study area, mafic formations of the Mako group are more common.

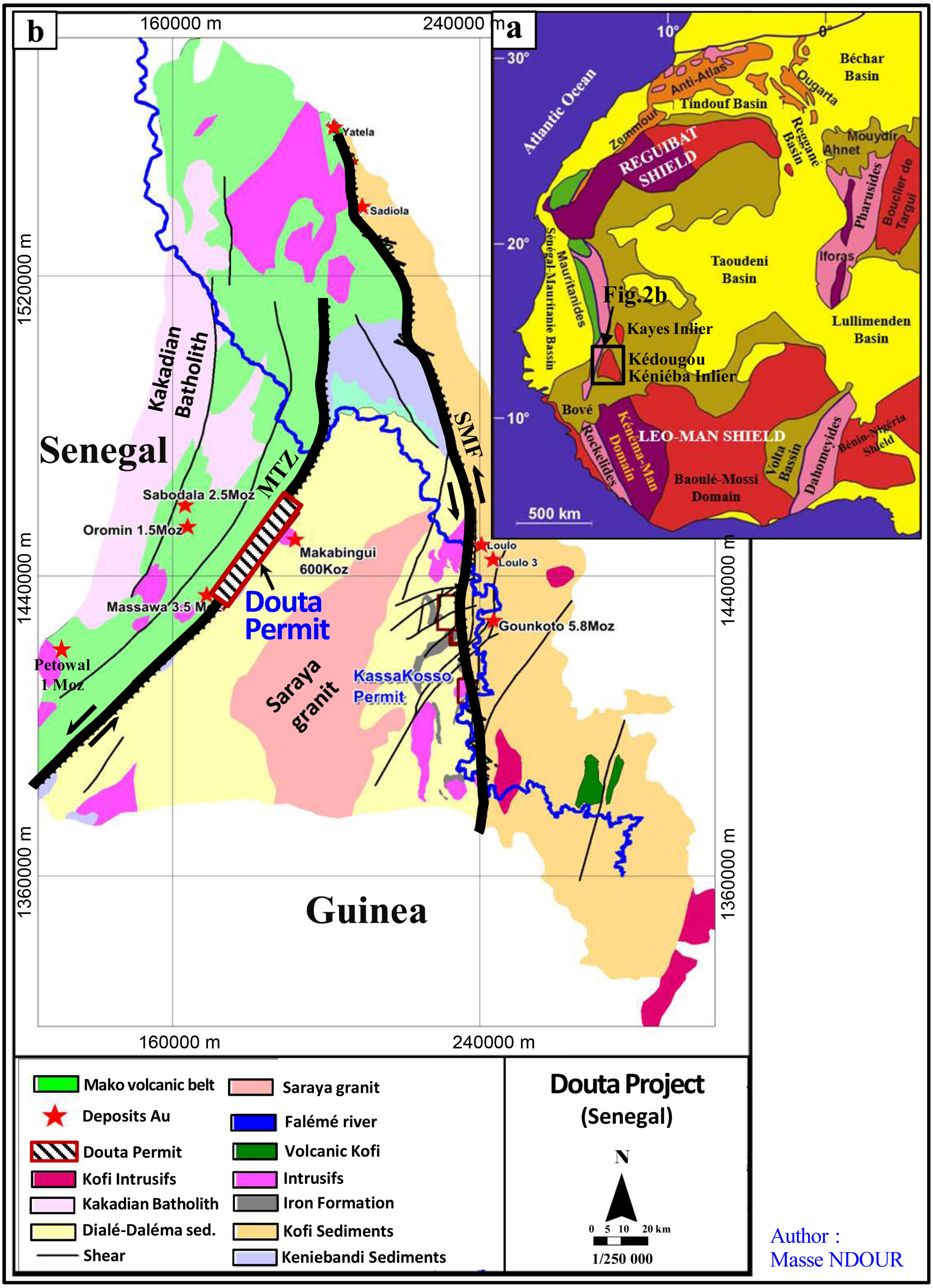

Figure 2. Geological context showing the position of the study area on (a) geological map of the West African Craton and (b) geological map of the Kédougou-Kéniéba Inlier.

3. Lithology and Petrography

The geology of the Douta permit is dominated by alterites (lateritic cuirass, colluvium, alluvium, erosion, etc.). These mask the rock formations in several places. For this reason, outcrops are quite rare, although a few can be observed. However, the trenches and the various Auger, RAB, RC and Core drilling have enabled us to better study the lithological, petrographic, structural, geochemical and metallogenic characteristics of the main facies in the study area.

The main lithological units in the study area, both in outcrop and in trenches and drillholes (Figure 3 & Figure 4) are meta-greywackes, shales, graphitic

Figure 3. Main lithological units in the Douta permit. ((a), (b)) core of greywackes; ((c), (d)) core of graphitic shales; (e) core of sedimentary breccias; (f) outcrop of cherts benches; (g) core of dolerite; ((h), (i) and (j)) outcrop and core of pegmatitic gabbros.

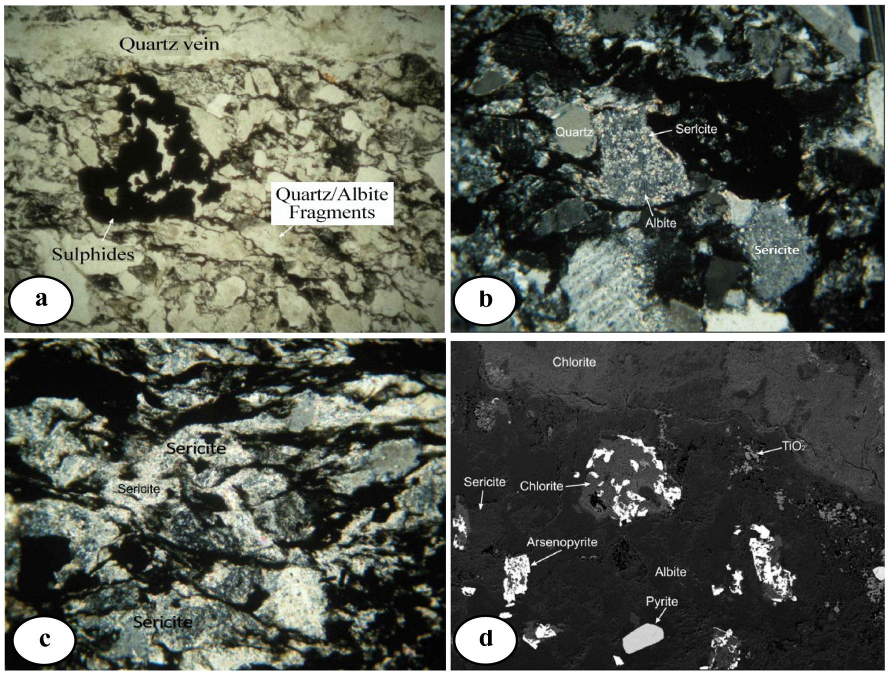

Figure 4. Microphotographs of greywackes in ((a), (b), (c)) transmitted polarized light and (d) backscattered electron image SEM illustrating the presence of quartz, albite, sericite, chlorite, muscovite, anatase, apatite, monazite and quartz veins/veinlets. ((b), (c)) show strong sericitization of albite. Sulphides (opaque/black in (a)) and (white in (d)) are disseminated in the rock.

shales, sedimentary breccias (conglomerates), tuffs, claystones, cherts and quartzites. These metasedimentary rocks constitute the host of numerous mafic magmatic rocks (dolerites and gabbros), as well as felsic rocks. Airborne geophysical data indicate strong potassic alteration that could be identified with subcrop granite at Makosa. Thin sections and polished sections were made in the United Kingdom (UK) for microscopic studies. These blades and polished sections correspond for the most part to core samples taken in the target zones (high-grade zones). Petrographic, mineralogical, microstructural and metallogenic studies were carried out using a conventional transmitted and reflected light microscopy, a Scanning Electron Microscope (SEM) and an X-Ray Diffractometer (XRD).

Meta-greywackes: They are more common in outcrops in the southern part of the study area. These metasediments present several hues (Figure 3(a) & Figure 3(b)) and a very variable grain size of the constituents. They consist of millimeter-sized grains of quartz and albite (felsic plagioclase) (Figure 4(a)), cemented in a fine matrix rich in sericite, muscovite and chlorite (Figure 4(b)). Albite minerals are affected by strong sericitization (Figure 4(b) & Figure 4(c)). Thus, albite can be completely replaced by sericite as illustrated in Figure 4(c). XRD analysis of these rocks confirms the presence of quartz, albite, muscovite, chlorite and calcite. Quartz and albite grains are generally monocrystalline and exhibit grain flattening and preferred orientation. Partially recrystallized chalcedony (cryptocrystalline quartz) is also present between quartz and albite clasts. Anatase and sphene are the two most common accessory minerals (Figure 4(d)). They were probably formed from the alteration of ferrotitanium oxides (ilmenite and titaniferous magnetite). The rock is traversed by several generations of veins/veinlets and is very rich in sulphides (Figure 3(a), Figure 3(b) & Figure 4(a)).

Shales: They are among the most abundant facies in the study area, both in outcrop and in drillholes. These facies are of varied origin and may be graphitic, pelitic or greywackous (Figure 3(c) & Figure 3(d)). These rocks are composed of very fine grains corresponding mainly to albite, quartz and graphite, in a matrix rich in sericite and chlorite (Figure 5(a) & Figure 5(b)). The shales are interbedded with the meta-grauwackes and the contact between the two lithologies is generally clear (Figure 5(a)). These metasediments are cut by several quartz/chlorite veins and veinlets, generally parallel to the schistosity, sometimes sheared (Figure 3(c) & Figure 3(d)). However, there are other veins intersecting the major structures. Fine and disseminated sulphides are also present in these rocks.

Sedimentary breccias: They are formed of sub-angular lithoclasts of variable size, cemented by a matrix very rich in silica or carbonate. These are sedimentary breccias. Lithoclasts are generally of variable nature and size, making them heterometric polygenic conglomerates (Figure 3(e)). Lithoclasts dominated by quartz, carbonate and fragments of other rocks are generally oriented and elongated in a preferential direction. The sulphides are dominated by pyrite and arsenopyrite. Sericite and hematite are also present in these rocks.

Cherts: These siliceous facies are widespread in the form of highly silicified benches often referred to as cherts or jaspes. They are more common in outcrops in the central part of the study area, where they are associated with greywackes, sandstones and quartzites (Figure 3(f)). They form small hills, generally elongated following the NE direction (N40). Their mineralogy is dominated by silica (chalcedony and/or opal).

Quartzites: They are more common in the southern part of the permit,

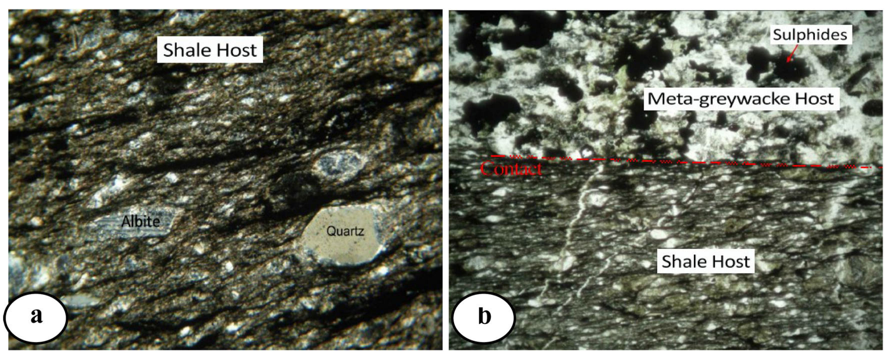

Figure 5. Transmitted polarized light microphotographs showing (a) the presence of quartz and albite grains surrounded by pressure shadows in a phyllosilicate-rich schistose matrix and (b) the clear contact between meta-greywackes and shales.

where they are associated with meta-greywackes. Elsewhere, they disappear beneath the lateritic cover. The mineralogy is dominated by quartz but other minerals such as pyrite, arsenopyrite, sericite and hematite are also present.

The various metasedimentary formations described above constitute the host of numerous mafic and felsic magmatic intrusions.

Magmatic intrusions: These correspond mainly to mafic sills and/or dykes of dolerites and gabbros cutting the metasediments (**Figures 3(g)-(j)**). These rocks outcrop discontinuously in several parts of the Douta permit (**Figure 3(h)** & **Figure 3(i)**). They have a microgranular to granular porphyritic texture. These formations are intersected at depth by the majority of drillholes (**Figure 3(g)** & **Figure 3(j)**). They are greenish-black hue, more or less speckled with white, and are composed of pyroxenes, plagioclases and secondarily, amphiboles and biotite. In the southern part of the permit, gabbro outcrops present a pegmatitic granular texture with plagioclase megacrysts up to 20 cm in size (**Figure 3(i)** & **Figure 3(j)**). Quartz veins are also noted in several areas of the permit.

4. Tectonic Structures

The Douta gold project is located along the Main Transcurrent Shear Zone (MTZ) [19] [37] [38] [55], which is a large sinistral ductile shear zone trending broadly NE-SW and becoming N-S towards the north. This regional structure has recorded a long and complex history of tectonic deformation, hydrothermal alteration and gold mineralization. The Douta perimeter is marked by shear corridors. The deformation is evidenced by the presence of numerous brittles, semi-ductile and ductile structures. These tectonic structures are essentially fractures, faults, veins and veinlets, schistosities, boudinages, lineations, shear zones, and so on. The structural study of the study area was based on field data and microscopic laboratory analyses.

4.1. Brittle to Semi-Ductile Structures

In the study area, brittle to semi-ductile deformation is one of the most dominant tectonics. It is marked by the presence of numerous structures such as fractures, faults, veins and veinlets, brittle-ductile shear zones and so on.

Fractures and faults are clearly visible in the field at outcrop and on cores samples, especially in competent rocks (gabbros, dolerites, greywackes, quartzites, etc.). Outcrop measurements on these structures gave N165-50SW, N35-62NW, N40-60SE, N60-74NW, N44-60SE and N58-88NW.

Veins and veinlets are also widespread structures in the Douta permit. They are found practically in all geological formations at outcrop, in trenches and in drilling cores (**Figures 6(a)-(f)**). For the most part, they correspond to quartz and/or carbonate or chlorite veins/veinlets. They essentially correspond to veins/veins of quartz and/or carbonate or chlorite. These structures are either parallel to the major structures or they intersect them.

Measurements taken on the veins in the trenches gave: N350-80NE, N340-

Figure 6. Photographs of veins observed (a) in outcrop, (b) in trenches and ((c), (d), (e), (f)) in drill cores from the Douta project. (c) Sinistral relay zone; ((e), (f)) Boudinaged quartz veins affected by a dextral and sinistral strike-slip respectively.

70NE, N100-10SW, N348-78NE, N300-68NE, N134-50SW. These veins are often anastomosing forming stockworks. They may also be fractured, boudinaged, sheared, in the form of relays or affected by dextral and/or sinistral strike-slip (**Figures 6(b)-(f)**). Microscopic studies show that quartz veins are often associated with chlorite (**Figure 7(a)**, **Figure 7(b)** & **Figure 7(d)**). Chlorite-rich veinlets are clearly visible in thin sections in the microscope (**Figure 7(e)**, **Figure 7(f)**). These chlorite veinlets are often associated with quartz or carbonate. In quartz, chlorite and carbonate veins, sulphides are generally found along the margins and rarely in the core (**Figure 7(a)**, **Figure 7(b)**, **Figure 7(e)** & **Figure 7(f)**).

4.2. Ductile Structures

The ductile deformation structures described in the Douta gold project mainly concern schistosity and/or foliation, lineation, boudinage, folds and ductile shear zones.

Schistosity is one of the dominant structures in the study area. It can be observed both in outcrop and in trenches and drillholes (**Figure 8(a)** and **Figure 8(b)**). One of the best exposures of this structure is found on an outcrop located

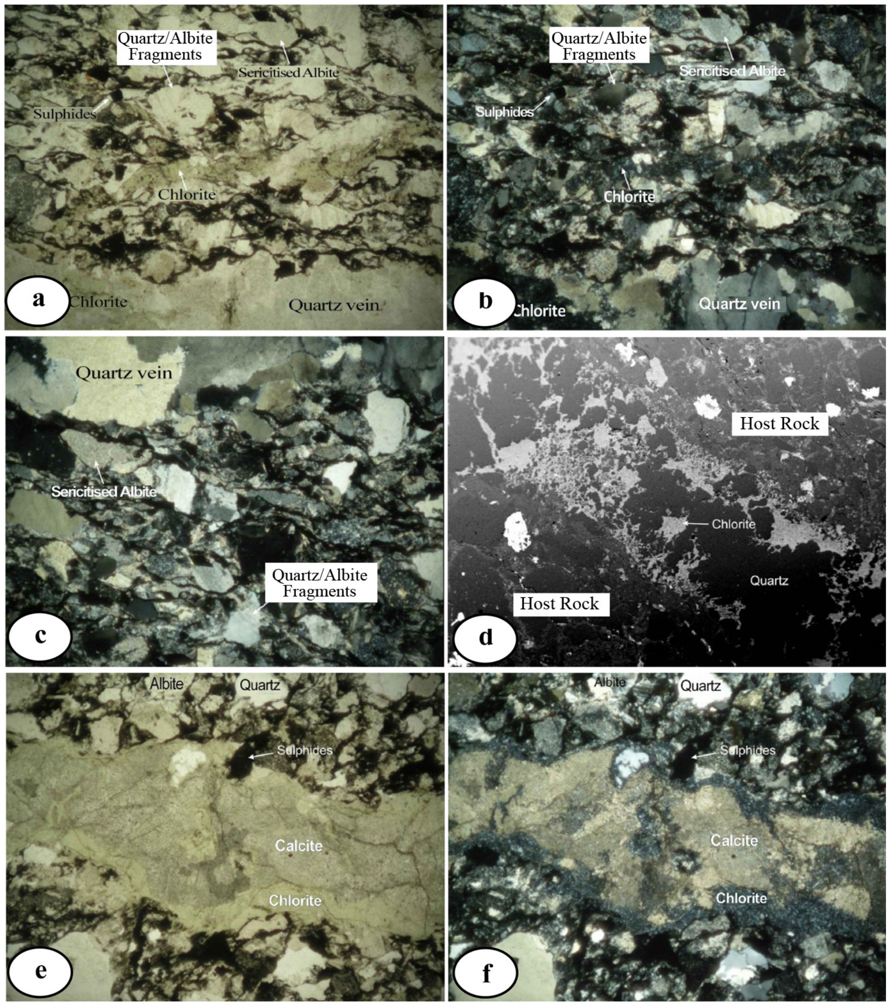

Figure 7. Transmitted and reflected light microphotographs, and backscattered electron SEM image of veins in the Douta permit showing ((a), (b), (c) and (d)) quartz veins often associated with chlorites and ((e), (f)) carbonate veins associated with chlorites and sulphides.

in the central part of the study area (Makosa prospect) (**Figure 8(a)** and **Figure 11**). It is formed of shales affected by a sinistral strike-slip. **Figure 8(b)** illustrates a folded S2 schistosity of the metasediments in the trenches. This S2 schistosity would be associated with the transcurrent deformation D2 affecting the geological formations of the two Birimian groups and which folds the first schistosity into a vast NE-SW trending anticline in the sedimentary package. Measurements taken on the schistosity in different places and at different levels (outcrop, trench, and so on) have given: N308-79NE, N310-76NE, N307-80NE, N290-85NE, N30-60SE, and N30-75SE. These data would seem to confirm the continuity and extension of this structure in the sector with practically an almost identical orientation. The schistosity is generally oriented NNE to NE in the Douta permit (**Figure 8(c)**).

Boudinages and lineations are also recurrent phenomena in the study area. Boudinages correspond to repeated and regular strictures of competent levels,

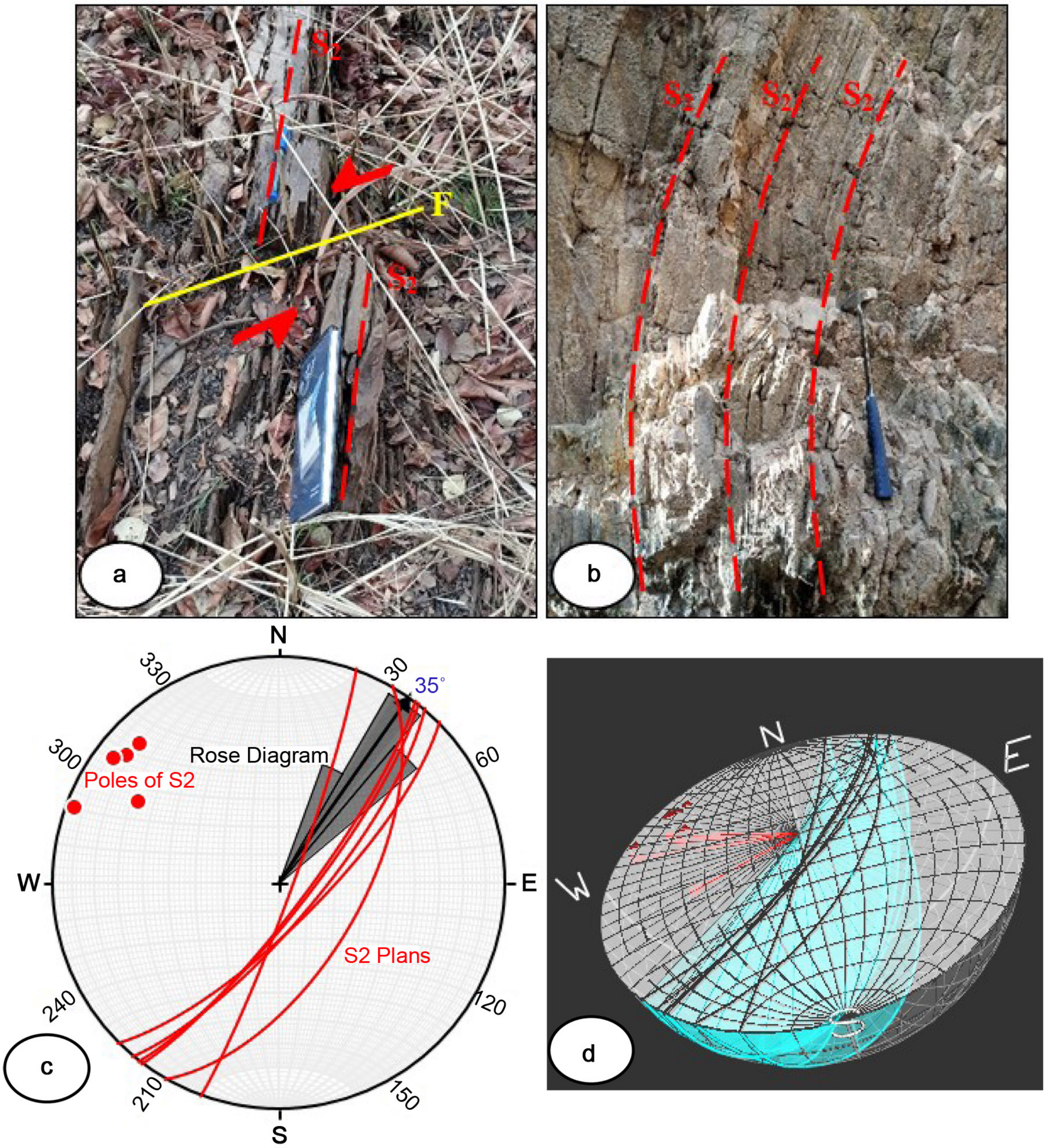

Figure 8. S2 Schistosity observed (a) in outcrop, (b) in trenches and (c) 2D, (d) 3D Stereographic representation and Rose diagram of schistosity measurements.

combined with foliation of incompetent levels. In the Douta permit, these structures are clearly visible on the drill cores and are illustrated in **Figures 9(a)-(c)** below. The latter correspond to boudinaged quartz veins within the metasedimentary formations.

Stretching lineations are also noted in the study area. They are materialized by the stretching of lithoclasts constituting the breccias, as clearly shown in **Figure 9(d)**.

In addition, ductile shear zones have been observed in the Maka prospect (northern part of the Douta permit). This is a shear zone affecting metasediments.

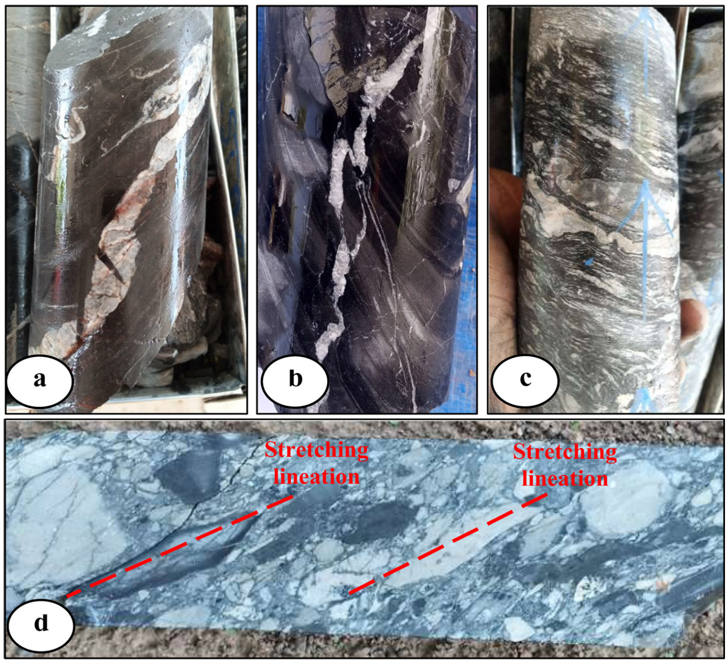

Figure 9. Boudinages ((a), (b), (c)) and lineations (d) observed in the Douta permit.

This zone extends over a distance of more than 150 meters. These ductile shear zones are most often characterized by mylonites. These highly deformed rocks can also be observed on the drilling cores. Thus, the intensity of this ductile deformation indicates the existence of very high stresses in the area. Several deformed and boudinaged veins and veinlets run through the rock. The rocks hosting these veins are highly mineralized and can contain up to 50 g/t gold, which demonstrates the fundamental role played by the structural in the control of gold mineralization, as we will see in the following section devoted to gold mineralization at Douta.

In summary, this tectonic study revealed two phases of deformation in the study area, D1 and D2, with the development of numerous tectonic structures. The movements are generally oriented in a NE-SW direction, with a sinistral sense and a principal stress σ1 oriented in the N-S direction.

5. Gold Mineralization in the Douta Permit

The study of the characteristics of gold mineralization in the KKI has provided an overview of the types of mineralization and their similarities to the orogenic model, but also their specificities and variations from one deposit to another. However, the majority of gold deposits discovered in the KKI remain concentrated for the moment in the Mako volcanic belt [27] [28] [30] [32] [34]. The aim here is to present the highlighting of the gold mineralization, the mineralized structures, the bearing lithologies and the paragenesis of the mineralization based on the results of geochemical prospecting, trenching and the various drillholes (Auger, RAB, RC and Diamond core).

5.1. Demonstration of Mineralization

- **Soil and Termites Geochemistry**

Several soil and termite mound geochemical surveys were carried out on the Douta perimeter. The main aim of this geochemical works was to define geochemical anomalies. The first soil geochemical survey (400 m × 50 m grid) was carried out in 2010 by International Mining Company (IMC). Sampling of termite mounds (200 m × 50 m grid) was carried out in areas not covered by soil geochemistry. The numerous samples collected during these various campaigns were sent to the ALS Global's laboratory in Bamako, Mali, which works in collaboration with the ALS Johannesburg, Gauteng, South Africa laboratory group, for analysis, the results of which are shown in Figure 10 below. These results

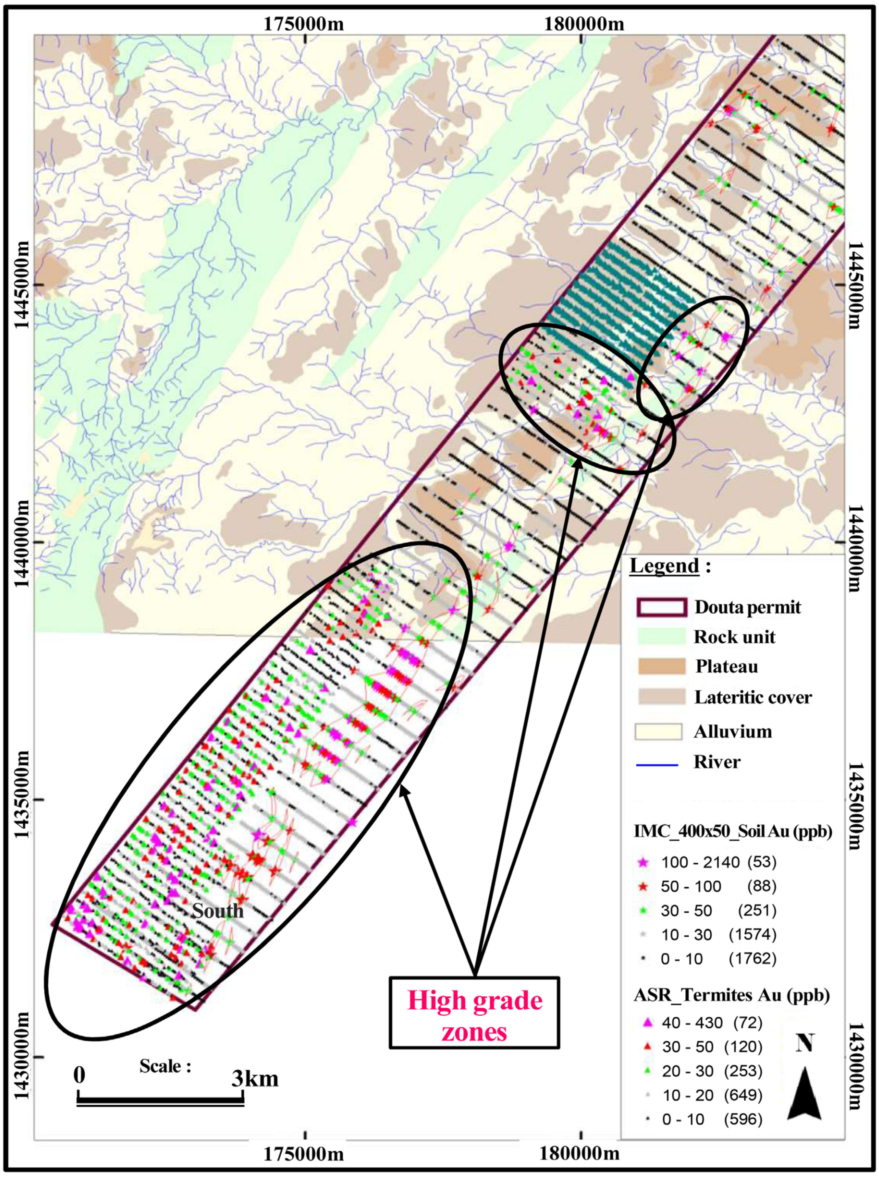

Figure 10. Regolith map compiled with soil and termite geochemistry results from the Douta permit.

gave very good values, particularly in the southern and northern parts of the permit, with grades ranging from 30 ppb to over 2000 ppb. More moderate grades (10 to 40 ppb) were obtained in the central part of the study area. These very encouraging results highlighted some very interesting geochemical anomalies that needed to be tested at depth. They also enabled us to subdivide the Douta permit into five (5) prospects from South to North: Makosa Tail, Makosa, Mansa, Maka and Sambara (Figure 11).

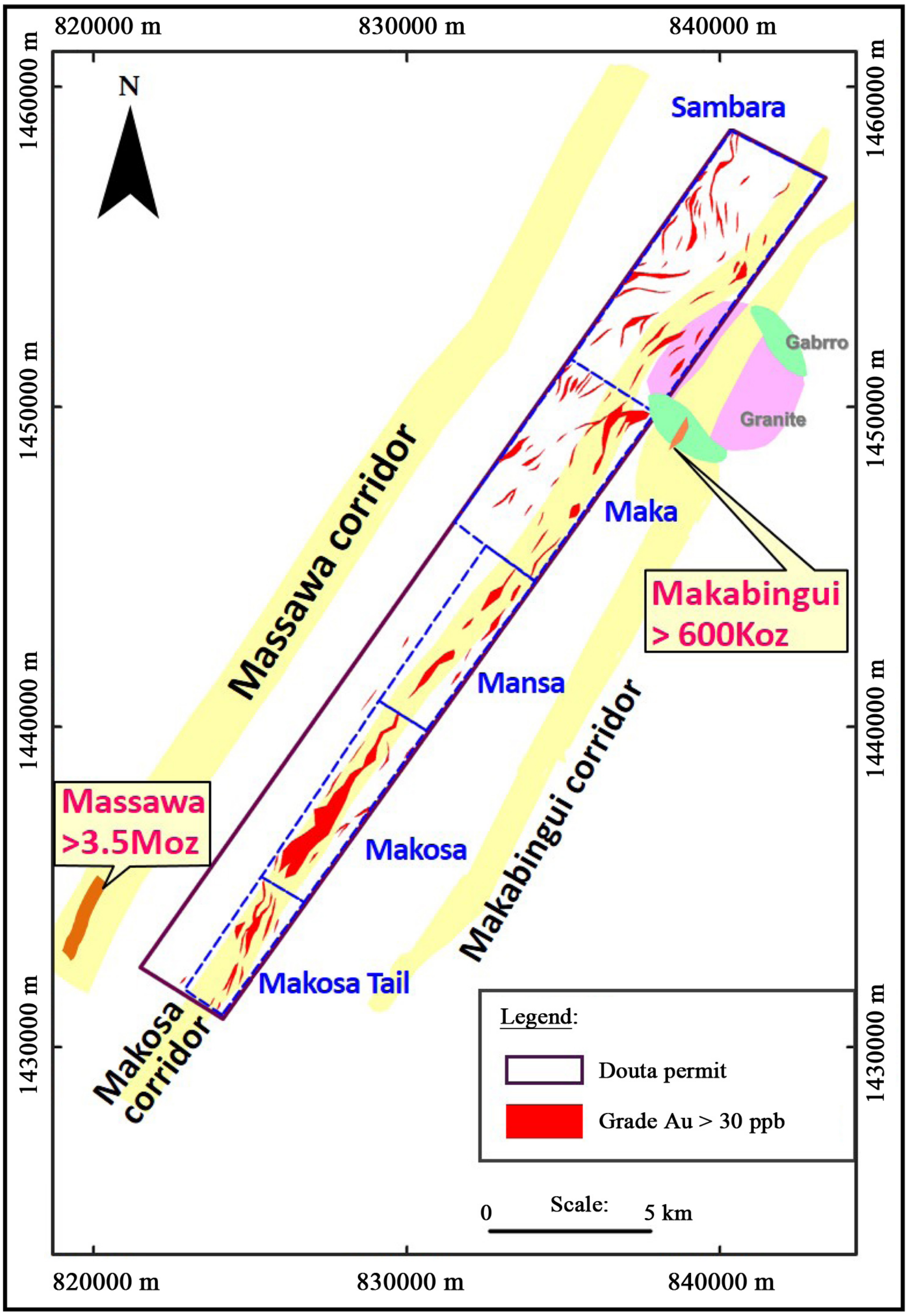

Figure 11. Map of the main prospects of the Douta permit.

- **Drilling**

The Douta gold project has been the subject of numerous geochemical, RAB, RC and Diamond core drilling campaigns. The RAB and RC drilling was carried out on the Makosa, Makosa Tail, Maka and Sambara prospects (Figure 11). The holes were drilled along the mineralized structure. The numerous samples collected were conditioned and sent to the laboratory for analysis. The satisfactory results obtained are presented in Table 1 and Figure 12, Figure 13 below. They confirm the continuity of gold mineralization over a minimum distance of 1000 meters to the North and South of Makosa.

In addition, following the interesting results obtained from the previous works described above, diamond drilling (DD) was carried out at several prospects on the Douta permit. The main aim of these holes was to gain a better understanding of the structures controlling the mineralization, in order to obtain a model of

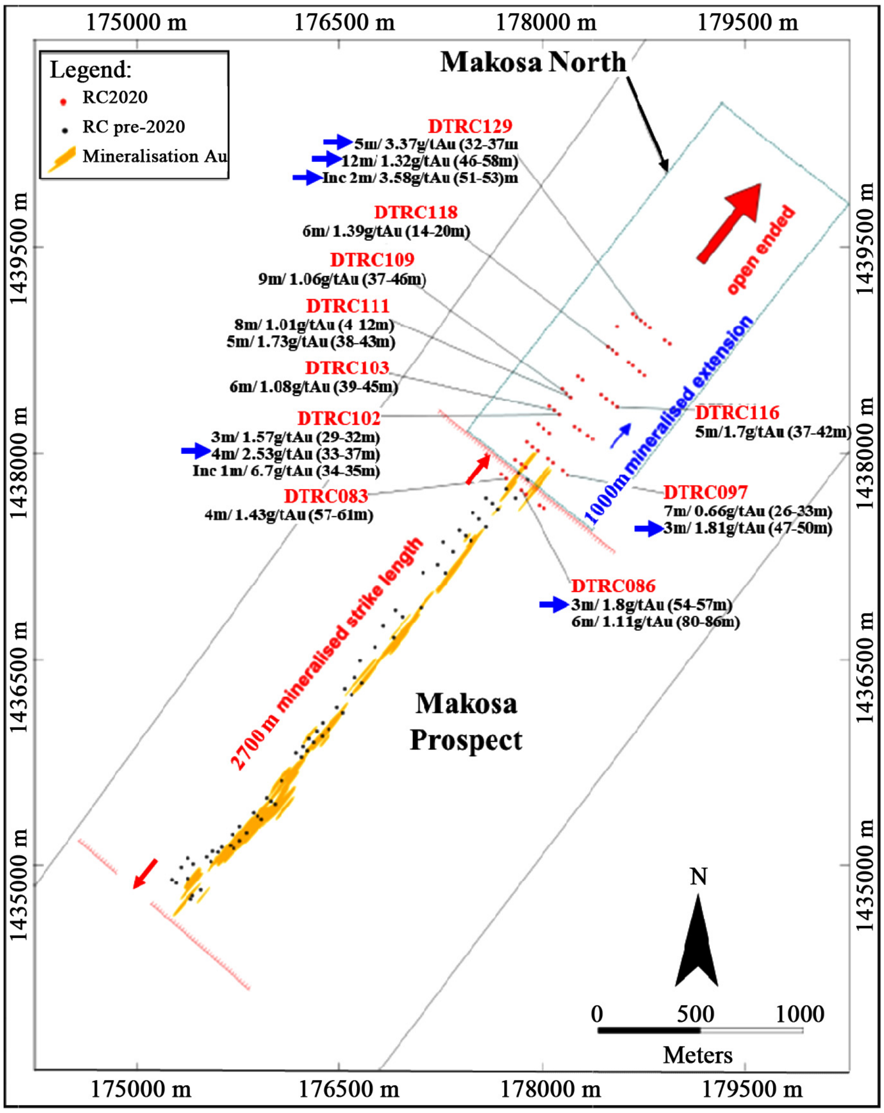

Figure 12. Interpretative summary map of RC 2020 drill results from the Makosa North area, showing the different intersections with cut-off grades above 0.5 g/t Au.

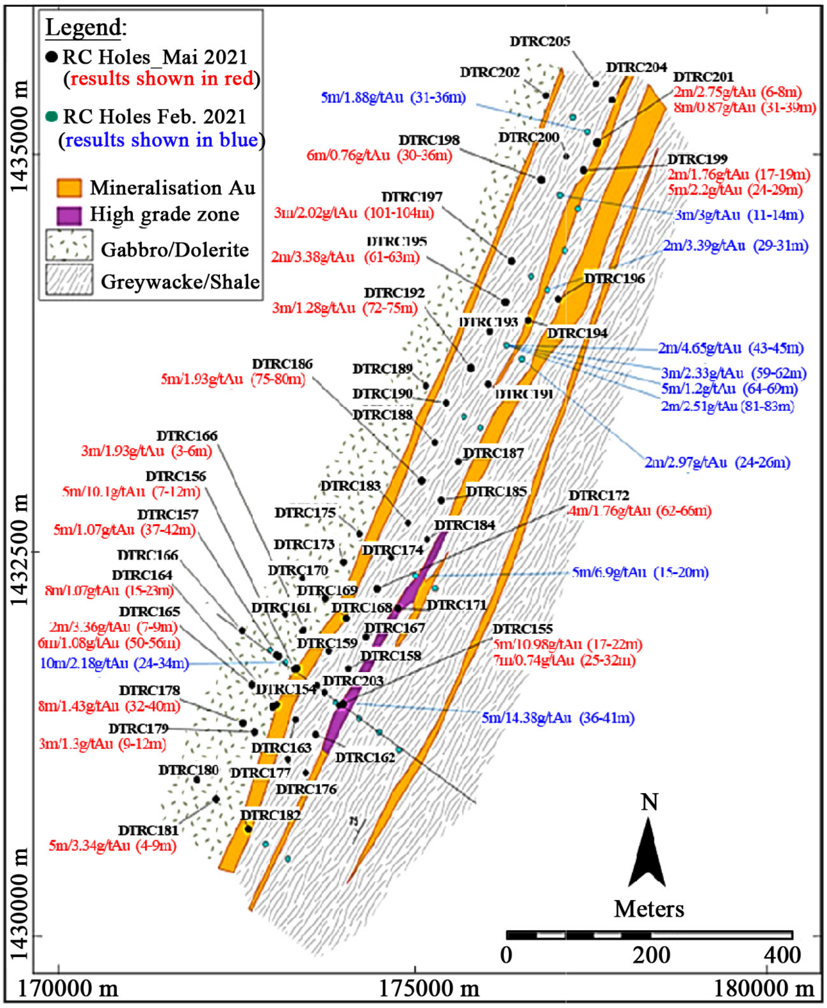

Figure 13. Map of RC 2021 drilling results from the Makosa Tail prospect, showing steeply dipping gold mineralization and geological formations.

Table 1. Results of some RC drillholes.

Hole ID	From (m)	To (m)	Interval (m)	Grade (g/tAu)
DTRC035	33 m	36 m	3 m	**13.2**
DTRC050	20 m	24 m	4 m	**3.0**
DTRC086	54 m	57 m	3 m	**1.8**
DTRC097	26 m	33 m	7 m	**0.66**
	47 m	50 m	3 m	**1.81**
DTRC102	29 m	32 m	3 m	**1.57**
	33 m	37 m	4 m	**2.53**
	34 m	35 m	1 m	**6.7**
DTRC129	32 m	37 m	5 m	**3.37**
	46 m	58 m	12 m	**1.32**
	51 m	53 m	2 m	**3.58**
DTRC155	17 m	22 m	5 m	**10.98**
DTRC156	7 m	12 m	5 m	**10.1**
DTRC181	4 m	9 m	5 m	**3.34**

this mineralization. The samples collected, conditioned and analyzed gave the results summarized in Table 2 and Figure 14 below. These results confirmed those of previous works.

5.2. Mineralized Structures

Most of the work carried out in the study area shows that mineralization is hosted by the Makosa shear corridor (Figure 15) and is associated with quartz, sericite, fine and disseminated pyrite and arsenopyrite (Figure 7, Figure 16 & Figure 17). This corridor and the mineralization have the same NE trend, with a subvertical dip (75˚ to 85˚ towards the NW). This suggests that this structure plays a key role in controlling the Douta gold mineralization. Quartz veins, often brecciated, boudinaged or sometimes forming stockworks and containing pyrite and arsenopyrite, are associated with this zone.

5.3. Host Lithologies of Mineralization

Exploration works carried out throughout the Douta permit has shown that mineralization is mainly hosted by two (2) metasedimentary units: meta-greywackes and shales. Indeed, the highest grades are mainly obtained in the meta-greywackes. Lower grades are found in the graphitic shales. This shows to a large extent that the porosity and mode of deformation of the host rock played important roles in the emplacement of mineralization. Thus, the coarser-grained

Table 2. Results of some diamond drilling holes.

Hole ID	From (m)	To (m)	Interval (m)	Grade (g/tAu)
DTDD0001	55	59.8	4.8	**8.2**
	56	58	2	**18.65**
	74	75	1	**1.63**
	82	83.9	1.9	**3.07**
DTDD0002	95	98	3	**1.33**
	106	107.88	1.88	**1.25**
DTDD0003	65.55	71	5.45	**0.85**
	87	91	4	**1.10**
DTDD0004	67	69	2	**3.00**
	74	84	10	**1.50**
	80	83	3	**2.50**
DTDD0009	11.5	13	1.5	**4.95**
	47	50.64	3.64	**2.98**
DTDD0011	90	91	1	**1.60**
	92	101	9	**1.52**

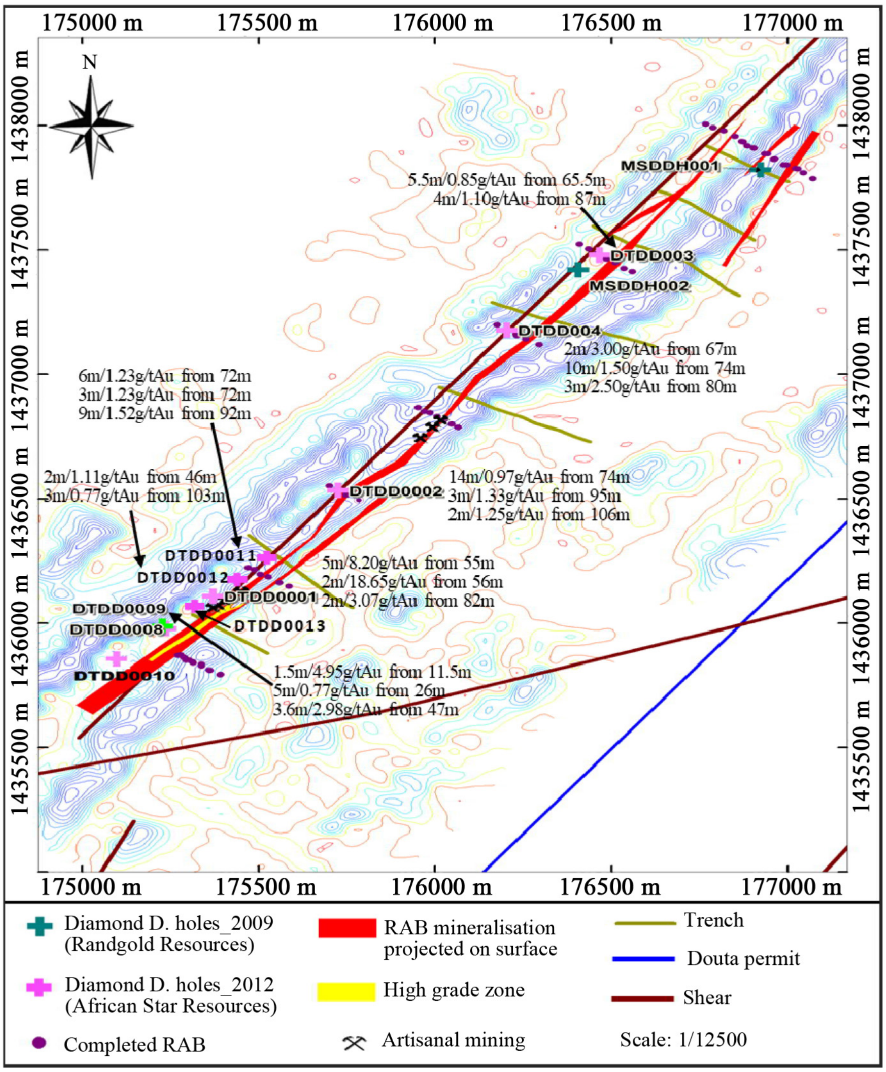

Figure 14. Program and results of diamond drilling carried out in the Makosa and Makosa Tail prospects, also showing trenching and complementary RAB drilling.

meta-greywackes deform more brittle than the fine-grained (phyllosilicates) graphitic shales, which deforms more ductile. The wall and roof of the mineralization consist of dolerite and gabbro dykes/sills, whose contact with the metasediments generally gives very good grades. However, the meta-greywackes and shales remain unmineralized in some places. Similarly, not all veins are mineralized. These remarks show that mineralization is not totally controlled by lithology. It would rather seem to be more influenced by the structural.

5.4. Paragenesis of Mineralization

In the Douta permit, mineralization is mainly arsenopyrite, pyrite and gold disseminated in metasediments. Pyrite is the dominant sulphide, but significant proportions of arsenopyrite are often observed in certain samples. Most of this gold mineralization occurs along the margin of quartz/carbonate and chlorite veins/veinlets, but sometimes it can also occur within or at the heart of veins

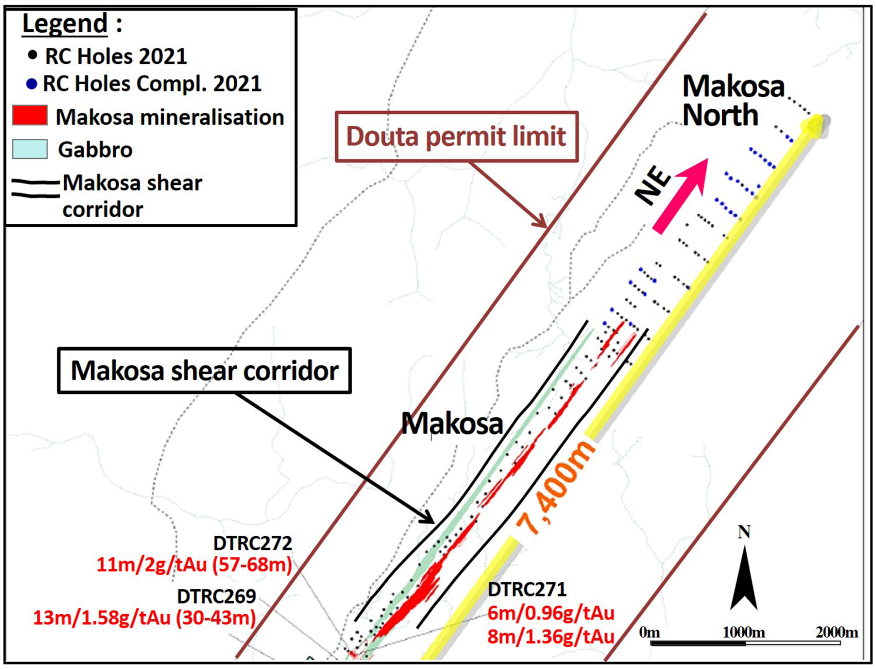

Figure 15. Map of the Makosa mineralization showing that it is carried by the Makosa shear corridor.

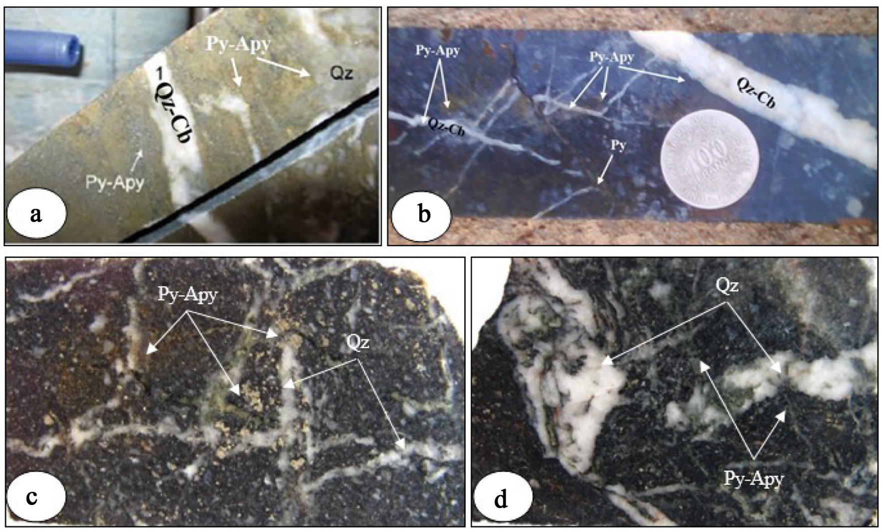

Figure 16. Gold-bearing pyrite and arsenopyrite mineralization observed in ((a), (c)) quartz-carbonate veins edges intersecting greywackes and ((b), (d)) intersecting graphitic shales. Py: pyrite; Apy: arsenopyrite; Qz: quartz and Cb: carbonate.

(Figure 16 & Figure 17). The emplacement of veins generally produces metamorphism in contact with the immediate host rock. Several generations of veins can be distinguished by the nature of their filling and their relationship with the host rock. Thus, veins parallel to the schistosity and containing fine and disseminated pyrites and arsenopyrites are highly mineralized. Pyrite, very abundant, appears to have formed independently of arsenopyrite and sometimes occurring in isolation of the arsenopyrite mineralization. Most often, it forms overgrowth

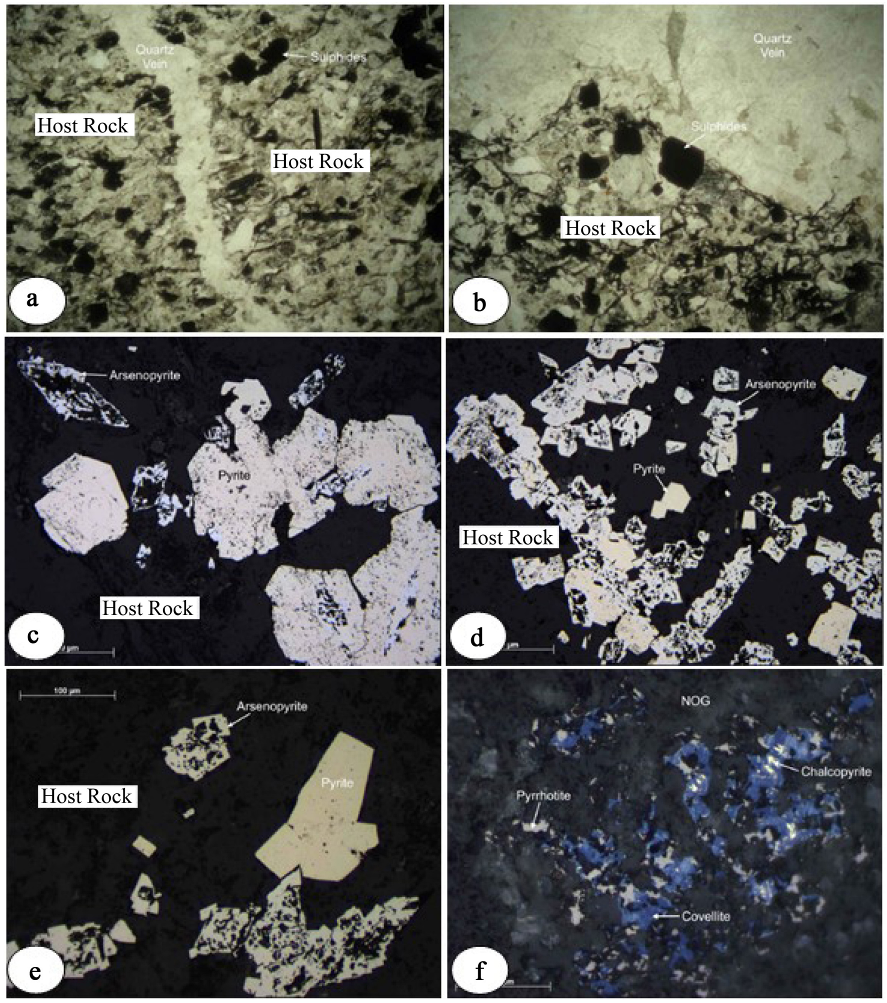

Figure 17. Transmitted light ((a), (b)), reflected light ((c), (d), (f)) and backscattered electron SEM image (e) microphotographs of veins and sulfides from the Douta project. ((a), (b)) quartz veinlet and vein with sulfides (opaque/black) present in the edges; ((c), (d) and (e)) euhedral pyrite (pale cream) forming outgrowths on poikiloblastic arsenopyrite (grey); (f) chalcopyrite, covellite and pyrrhotite in graphitic shales.

on the earlier formed arsenopyrite crystals (Figures 17(c)-(e)). In some cases, the pyrite envelops or completely encapsulating the arsenopyrite, as clearly illustrated in Figures 17(c)-(e). Pyrite is poecilitic in nature, containing few inclusions and generally forms either disseminated euhedral crystals or aggregates of crystals. The pyrite crystals exhibit a generally coarser grain size relative to the arsenopyrite, with discrete crystals often exceeding 300 µm (Figure 17(c) and Figure 17(e)). Arsenopyrite also occurs as euhedral rhomb-shaped crystals with discrete crystals rarely exceeding 300 µm (Figures 17(c)-(e)). The arsenopyrite crystals commonly contain abundant inclusions of fine-grained sericite and/or chlorite, possibly indicating poikiloblastic crystal growth whereby gangue inclusions are trapped in the host mineral during development of the arsenopyrite (Figures 17(c)-(e)). Arsenopyrite typically exhibits complex pseudomorphous textures and represents the first major phase of gold mineralization. This is corroborated by textural evidence that pyrite generally forms an overgrowth on the earlier formed arsenopyrite crystals (**Figures 17(c)-(e)**), in contrast to Massawa project, where the automorphic arsenopyrite clearly crystallizes both within and around the pyrite and represents the first phase of mineralization. Examination of the fine-grained sulphides within the graphitic shale confirmed the presence of chalcopyrite, covellite and pyrrhotite (**Figure 17(f)**).

6. Discussion and Conclusion

The Douta gold mineralization is hosted by Birimian metasediments (mainly meta-greywackes and shales) of eastern Senegal. It is formed by metamorphic and hydrothermal processes thought to be related to the Sambarabougou granitic intrusion. Gold is associated with a paragenesis consisting of quartz/carbonate-sericite-epidote-fine and disseminated pyrite and arsenopyrite ± albite ± chlorite ± hematite (**Figure 4**, **Figure 5**, **Figure 7** & **Figure 17**). In fact, all the alteration phases and associated mineral parageneses are located in ductile to ductile-brittle deformation corridors associated with veins such as the NE Makosa shear corridor shown in **Figure 15**. The mineralization trends NE, *i.e*. sub-parallel to the Makosa shear zone, and dips steeply (75˚ to 85˚ to the NW) (**Figures 10-19**). This demonstrates the fundamental role played by the structural in controlling mineralization at Douta. In addition, the gold mineralization is mainly hosted by two (2) lithologies (meta-greywackes and shales). The numerous results obtained argue in favor of lithostructural control of the Douta gold mineralization and its similarity to the orogenic and hydrothermal deposits model. This model of gold vein mineralization associated with disseminated sulphides would correlate with type 5 in the classification of Milési *et al*. [19], which corresponds to the late-orogenic deposit in the classification of Milési *et al*. [20] (**Figure 18**). It would be comparable to type 4 (veins in a sedimentary host) and type 3 (unconformable veins, stockworks in a volcano-sedimentary or sedimentary context) in the classifications drawn up by Boyle [21] and Bache [13] respectively. This type of deposit has been reported in Canada (*Noranda*, *Lamaque*, *and Madsen Red Lake*), California in the USA (*Mother Lode*), Australia (*Kalgoorlie*, *Bendigo-Ballarat*) and Zimbabwe (*Cam and Motor*) [13]. It also would correlate with type 2 in the classification of Béziat *et al*. [24], which is based on the geometry and style of mineralization. The mineralized veins are thought to have developed in a structural context subsequent to the development of the regional structures. This organization clearly demonstrates the late-orogenic character of Douta's gold mineralization.

The gold mineralization of Douta presents characteristics comparable to those of other deposits in the KKI, especially in terms of mineralization type, mineralized structures, nature of host rocks and metalliferous paragenesis. Indeed, the lithostructural control of the Douta gold mineralization is similar to that of the Massawa (>4 Moz) [40] [56] [57] [58] and Makabingui (>1 Moz) [54] [59] [60] deposits located 4 km to the West and 1.5 km to the East respectively. Thus, the

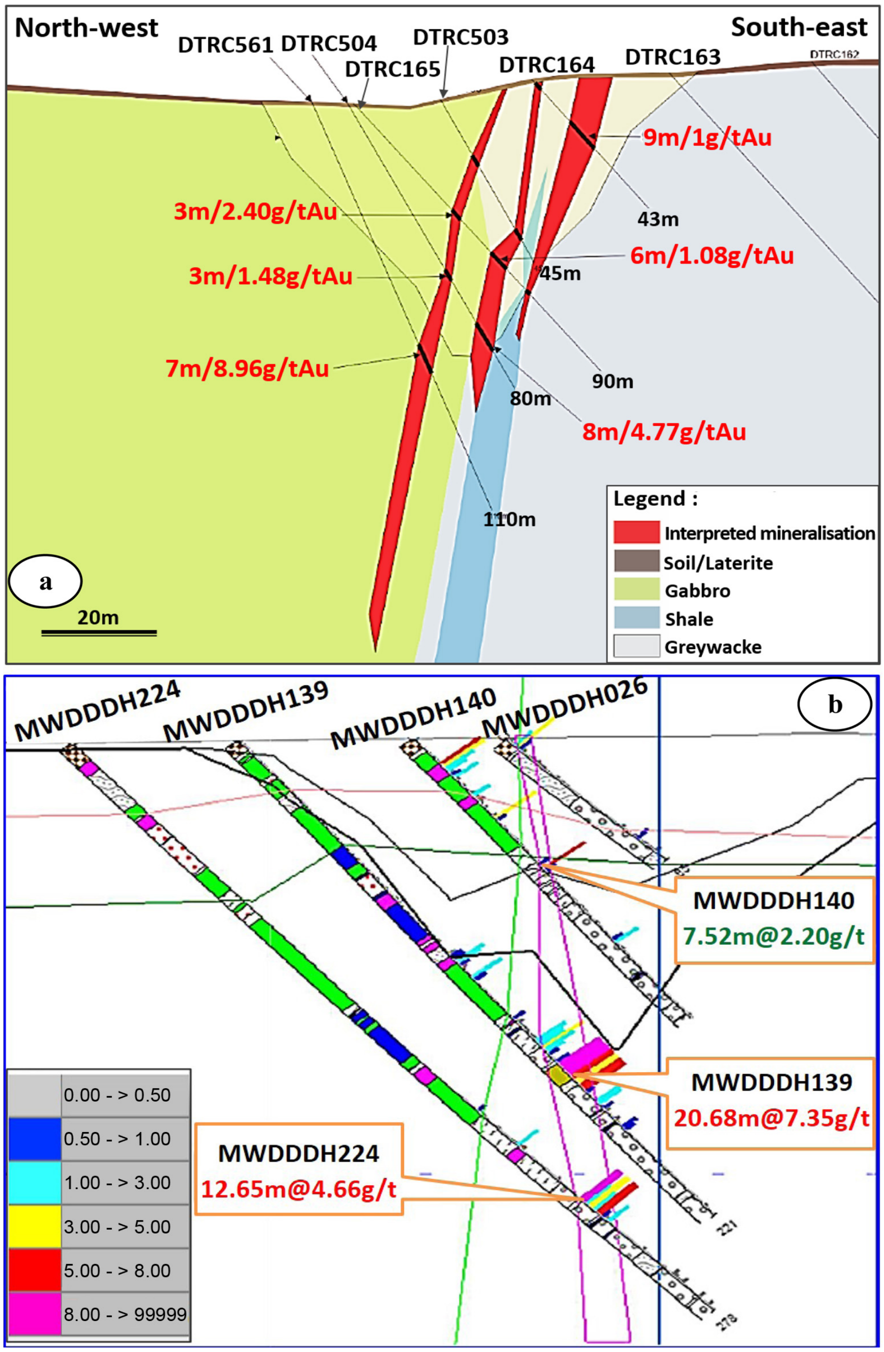

Figure 18. 2D representation of the Douta mineralization model (a) in comparison to the Massawa model (b) [58].

characteristic parageneses of these deposits are generally rich in quartz, carbonate, sericite and sulphides (pyrites and arsenopyrites). The fine, disseminated pyrites and arsenopyrites that characterize much of the mineralization at Massawa are highly visible at Douta. Their presence is indicative of gold mineralization in the Douta project. However, studies show that pyrite crystallized from arsenopyrite at Douta, whereas at Massawa, arsenopyrite predates pyrite. Similar mineral parageneses have also been reported in other KKI deposits including Sabodala [26] [32] [34] [61] [62] [63] [64].

The brittle-ductile to ductile deformation structures controlling the mineralization at Douta are similar to those described in the Sabodala, Petowal and Boto deposits by Sylla [34], Dème [62] and Lincoln *et al.* [64], respectively. **Figure 18** compares the 2D mineralization model for Douta with that for Massawa. These models show many similarities, especially with regard to the geometry of the mineralization. The NNE to NE orientation and subvertical dip (75˚ to 85˚ to the NW direction) of the Douta mineralization (**Figure 18(a)** & **Figure (19)**) is almost identical to that of Massawa (**Figure 18(b)**). It clearly confirms the parallelism with the majors' structures-oriented NNE to NE in the Douta perimeter. **Figure 19** is a 3D model of gold mineralization at Douta. It shows four (4) mineralization lodes with variable grades, all oriented NNE to NE and exhibiting a subvertical dip.

At the WAC scale, similar features appear in a certain number of deposits [31], notably in the Kalana metasediments [24] [65] [66], the Loulo [20] [27] [28] [67] and Yatela [68] deposits in Mali, the Wassa and Julie deposits [5] [6] [69] [70] in Ghana, the Poura sandstones in Burkina Faso.

However, some variations, especially in relation to the nature of the host rocks and the age of emplacement, are worth noting. According to Perrouty *et al.* [5] and Parra-Avila *et al.* [6], the gold mineralization at Wassa is pre- to syn-D1 (Eoeburnean) and was emplaced between 2187 and 2158 Ma, unlike that at Douta, which presents a metamorphic and late-orogenic character, correlating with the D2 deformation phase (**Figure 20**). Indeed, most of the vein-type WAC

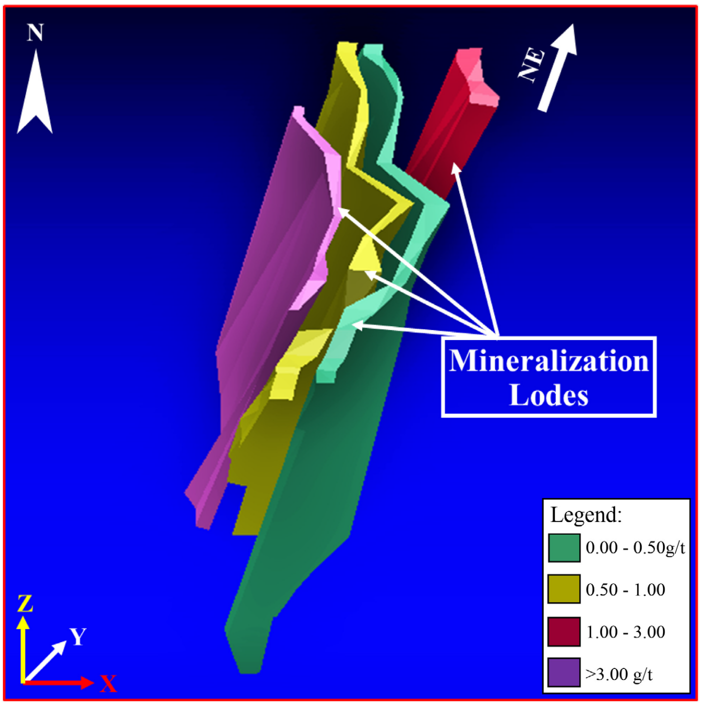

Figure 19. 3D model of Douta mineralization showing four (4) mineralization lodes with NNE to NE orientation and subvertical dip.

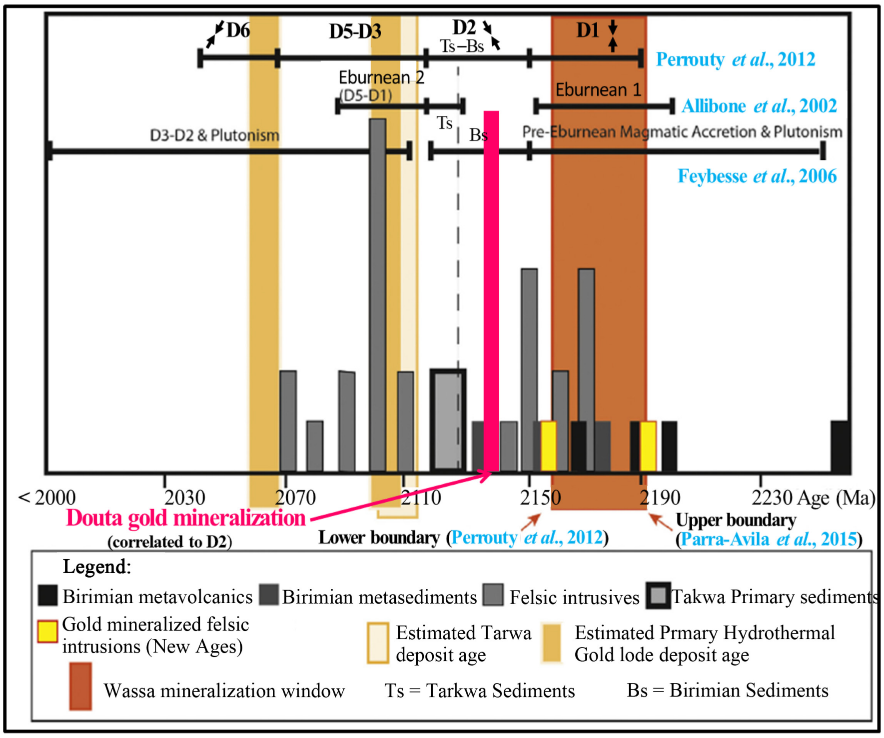

Figure 20. Summary diagram of tectonic events, ages and mineralization in the Ashanti belt (WAC) ([3] [5] [6] [69] [73]) showing the relative position of the late-orogenic mineralization at Douta.

deposits [3] [19] [20] [24] correspond to steeply dipping quartz veins or families of veins with an orientation parallel to that of the regional foliation [71].

Comparable features have also been described in Central Africa, particularly in the Archean Etéké belt in Gabon, where mineralization is contained in veins forming stockworks associated with a hydrothermal event [72].

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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